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TRACOR'S

MUTUAL INTERFERENCE, AND ACOUSTIC COUNTERMEASURES  
ANALYSIS CAPABILITIES.

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## 1.0 INTRODUCTION

Over the past three years TRACOR's System Technology Division scientists and engineers have been engaged in countermeasures susceptibility studies for several sonar systems. In addition, STD personnel have conducted studies pertaining to the effects of mutual interference (MI) for two surface ship sonar systems. This work is usually composed of three parts which are (a) definition of the interference environment, (b) determination of susceptibility, and (c) design of counter-countermeasures or anti-MI fixes. Generally, the methods used to determine the effects of interference, whether countermeasures of mutual interference, are one or a combination of the following:

- 1) mathematical analysis,
- 2) computer simulation, and
- 3) psychophysical experimentation.

Our efforts have included such sonars as the AN/SQQ-23 (PAIR), the AN/SQS-26 AX, BX and CX, and the AN/BQR-2 DIMUS which collectively encompass the following receiving subsystems.

- 1) Serial DIMUS (Passive Search)
- 2) PADLOC (Passive Search)
- 3) Sector Scan Indicator (Active Track)
- 4) Scanned PPI (Active Search)
- 5) Wave period processor (Active search)
- 6) Linear replica correlators (Active Search)
- 7) Comb filter bank/OR-gate (High Doppler Active Search)
- 8) Preformed beam/energy detectors (Active Search)



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The first step in these studies, prior to any analytical effort, is to become familiar with the acoustic countermeasures capability of the U. S. Navy and (to the extent that our intelligence estimates will permit) the enemy countermeasures threat. This type of activity is required so it will be possible to define a realistic countermeasures threat for the U. S. sonar systems under examination.

The third element of our approach to treating the countermeasures problem is the consideration of possible counter-countermeasures which would serve to reduce the performance degradation. In the case of the mutual interference problem, where we have control over both the source of interference as well as the victim, we have recommended to the Navy numerous design guidelines and modifications to both the sonar transmitter and receiving subsystems which, if implemented, would reduce the severity of the interference problem.

Counter-countermeasures and mutual interference reduction have been approached primarily from the standpoint of hardware modifications. However, we have also given attention to the areas of operating doctrine and operator training since both of these can serve to reduce the effects of both countermeasures and mutual interference.

In the remaining part of this description we will describe the methods that are used to assess the effects of both acoustic countermeasures and mutual interference.



## 2.0 TECHNICAL APPROACH

As mentioned previously, our method of approach is generally composed of one or a combination of mathematical analysis, computer simulation and psychophysical studies based on observer-display experiments. These three approaches will be described here. But first let us examine what we wish to determine regarding either countermeasures susceptibility or mutual interference effects.

Basically what we are after is a quantitative measure of the degree to which the performance of each sonar receiver is degraded by the presence of either countermeasures or mutual interference. Specifically, if the function of the receiver is detection, then under normal conditions (i.e., no interference) there will be some target-to-sonar range at which detection may be said to occur. (This is often taken to be the target range at which the signal-plus-noise will mark the display with a specified probability given that the clutter marking probability is fixed at a specified value.) Let us call this range  $R_{DN}$  to denote that this is the detection range under normal conditions. This then, is a measure of the performance of the receiver under some specified set of "normal environmental conditions" such as layer depth, sea state, target strength, etc.

When interference of a continuous type is introduced into the environment, the effect is to increase the background level against which the target echo must be detected. Thus, to restore the probability of detection to the original specified value, the target signal level must be increased. This requires that the target be moved to a closer range. Once this range is attained, the signal-to-background ratio is sufficient to give the required detection probability. The target range at which this occurs is called  $R_{DJ}$  to denote that this is the detection range under jammer (or interference) conditions.



The degree to which receiver performance is degraded by interference is defined to be  $R_{DJ}/R_{DN}$ . This ratio can vary from unity, when  $R_{DJ} = R_{DN}$ , to zero, when  $R_{DJ}=0$ .  $R_{DJ}/R_{DN}$  depends on several factors, two of the most important ones being the range of the jamming (interference) source,  $R_J$ , jammer-to-target relative bearing angle  $\theta_{JT}$ . Thus, by determining the ratio  $R_{DJ}/R_{DN}$  for various values of  $R_J$  and  $\theta_{JT}$  it is possible to obtain a quantitative assessment of the performance degradation due to jamming. Such an assessment is shown in Fig. 1. Within the envelope shown in this figure one can expect to find what the performance of the search receiver would be for any relative bearing angle between the jammer and target since the boundaries of the envelope represent the maximum and minimum degradations that would hold for each jammer range.

In fact this method of measuring performance degradation can be applied to receiving systems whose functions are localization, tracking, or classification. For example, in a tracking receiver, all that we have to do is specify (by analysis) the target range required for signal-to-noise ratio to be large enough to give the required tracking accuracy with a specified probability.\* The introduction of interference or jamming into the background will require a higher signal power for the same tracking accuracy and hence a closer target range. Hence we can plot  $R_{TJ}/R_{TN}$  versus  $R_J$  with  $\theta_{JT}$  as a parameter.

This is actually only one of several ways of defining performance and measuring the decrease in performance due to continuous countermeasures or mutual interference. Another approach that we have taken is to measure the increased time

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\*Tracking errors are random variables and hence are described by probability distributions. It is thus required that in addition to stating a tracking accuracy, one must specify the probability that this accuracy will be achieved.



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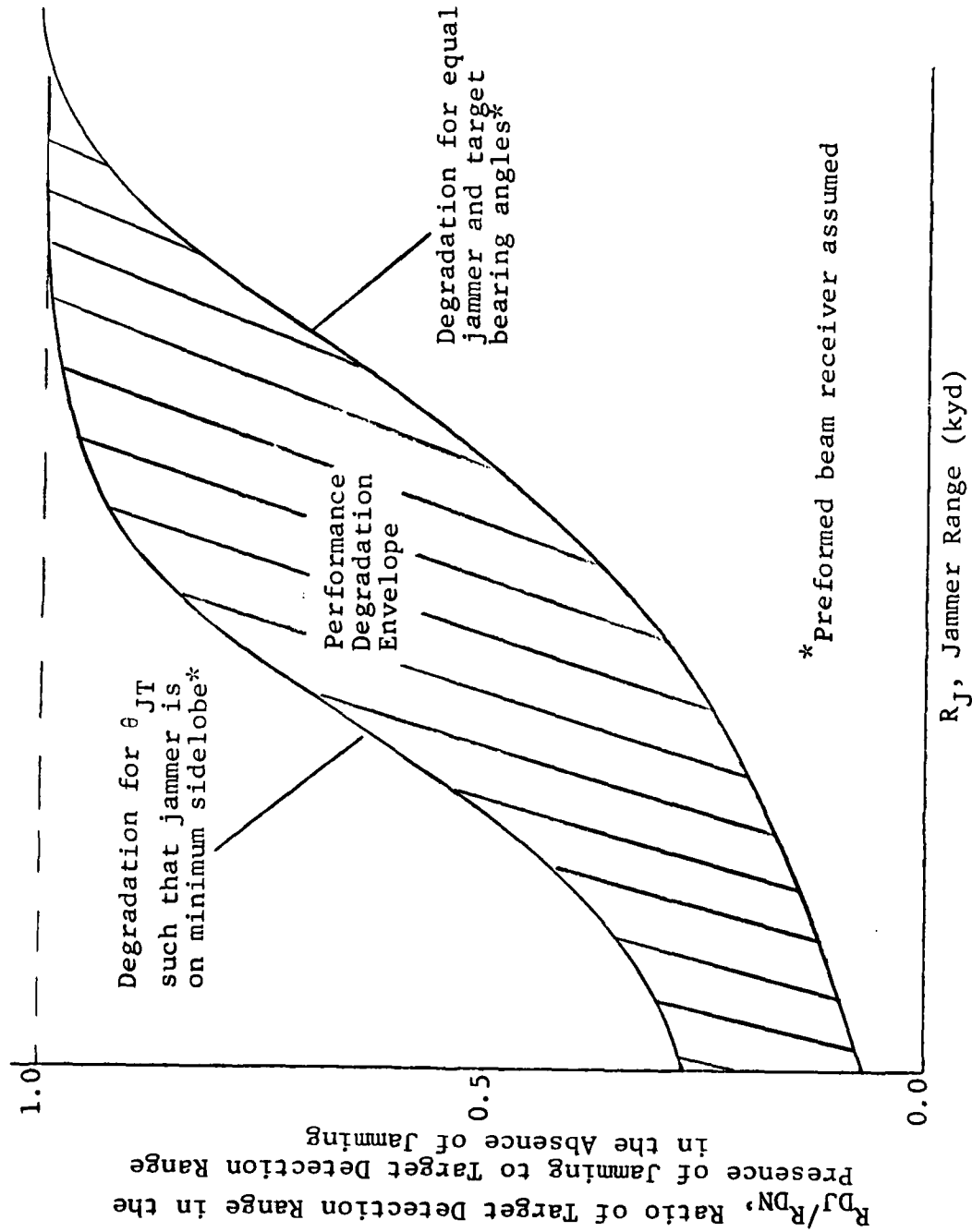


FIG. 1 - PERFORMANCE DEGRADATION FOR SEARCH RECEIVER DUE TO JAMMING



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required to detect. This can be done for active systems in terms of the number of extra ping cycles required, or in the case of passive systems in terms of the increased number of updates required for detection. The three methods of arriving at these performance assessments are discussed next.

## 2.1 Mathematical Analysis

When it is possible to analyze performance this is usually the least expensive route to take. An example will suffice to demonstrate this approach.

Consider an active search receiver whose output has been or can be mathematically modelled. This model allows us to generate a family of curves which are actually the complements of the distribution functions at the receiver output for various signal-to-noise ratios. Such a family is shown in Fig. 2. With these curves it is possible to find the signal-to-noise ratio at the beamformer output  $(S/N)_0$  that is required to give, say, a 0.50 probability of "detection" (signal-plus-noise marking) for the clutter probability,  $P_c$ , that is specified for the display. This is shown by the dashed lines, the vertical one of which is the required threshold. The signal-plus-noise curve that crosses this threshold at 0.5 corresponds to required signal-to-noise ratio for detection, or alternatively the signal-to-noise ratio required to produce the display mark(s) that the operator requires before he will call a detection.\*

The next step is to obtain a band level plot such as the one shown in Fig. 3. This group of band level power plots shows the composite background without jamming (reverberation-plus-self noise) and the composite background with the jammer at one range

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\*The latter approach allows a calculation of the cumulative probability of detection as a function of time.





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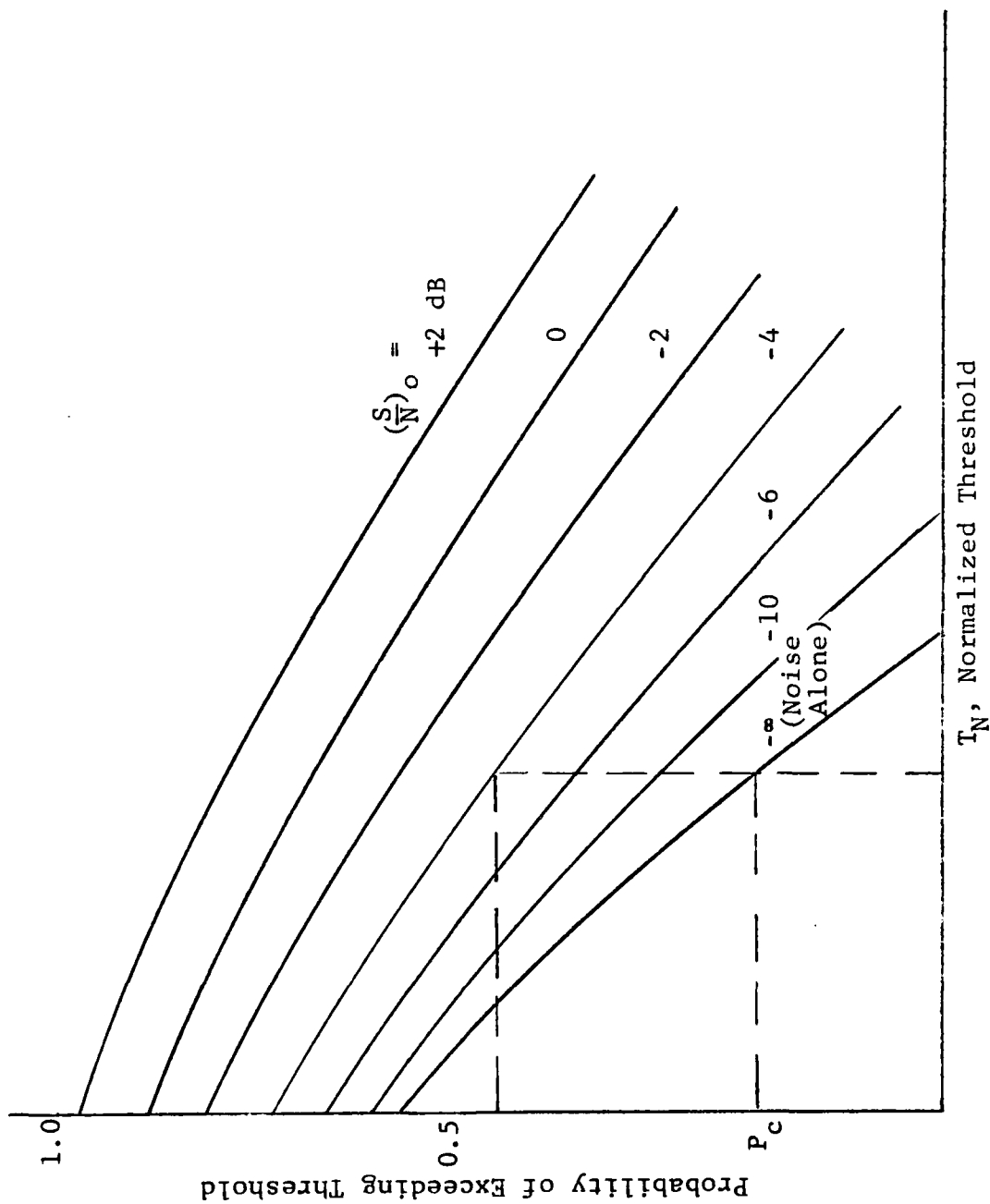


FIG. 2 - PROBABILITY OF EXCEEDING THRESHOLD VERSUS THRESHOLD



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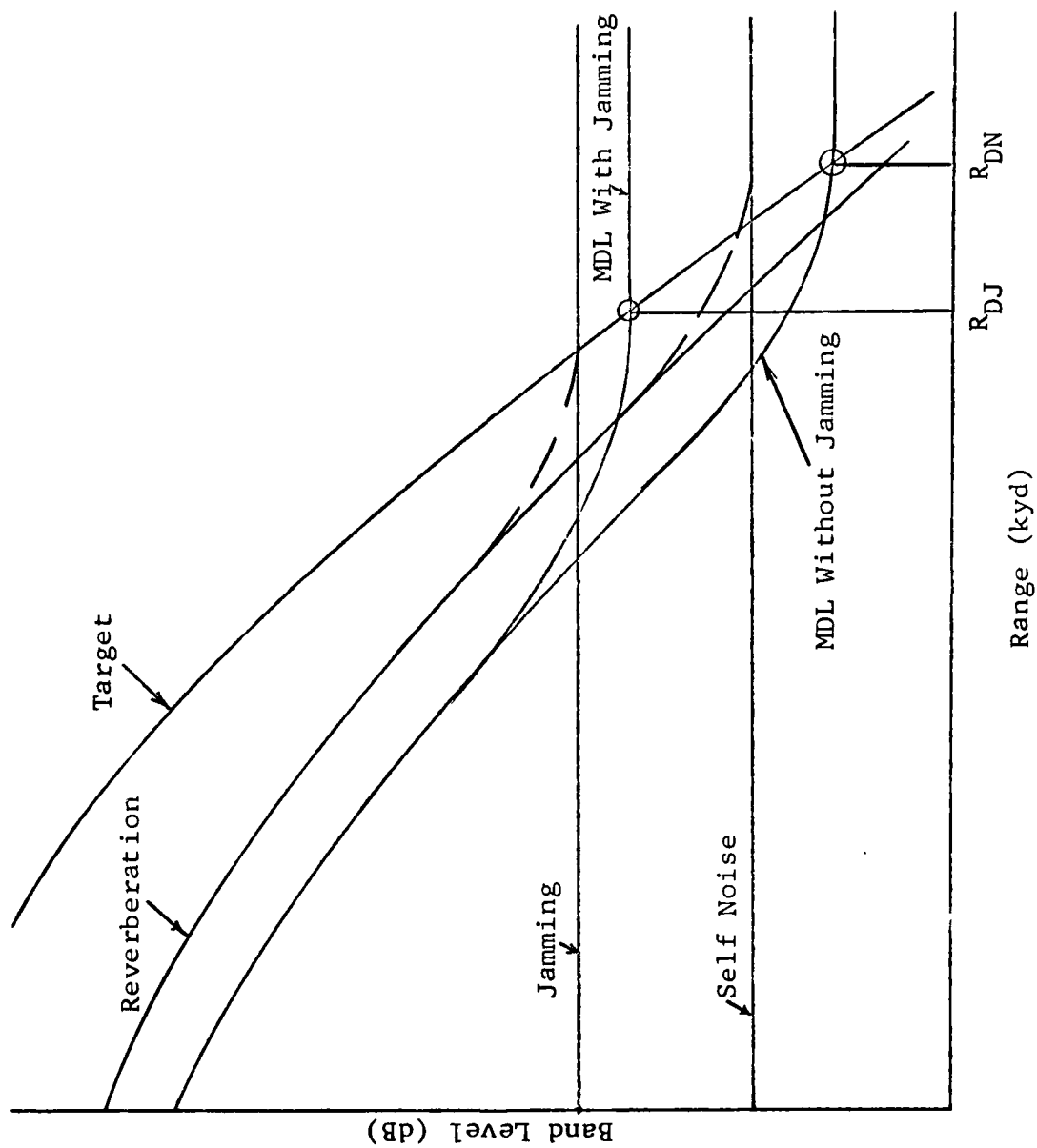


FIG. 3 - BAND LEVEL PLOTS SHOWING METHOD OF DETERMINING DETECTION RANGE WITH AND WITHOUT JAMMING



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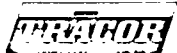
(reverberation-plus-self noise-plus-jamming). The target level is also shown, as are the minimum detectable levels which are the power levels relative to the composite background levels required for detection as determined from curves such as those shown in Fig. 2. From these curves we find the quantities  $R_{DN}$  and  $R_{DJ}$  for each  $R_J$  and  $\theta_{TJ}$  of interest to us.

## 2.2 Simulation

Often it is not possible to obtain a mathematical description of the receiver output. In such cases it is necessary to conduct a simulation wherein the sonar receiver is implemented in the digital computer and self-noise, plus jamming signal, plus target signal are input to the simulation. The receiver output is then analyzed statistically in order to obtain estimates of the curves shown in Fig. 2. For this purpose TRACOR has a computer software system known as TIMFAX. A description of this system is given in the Appendix. It should be noted that this system includes so called black boxes which provide simulations of virtually every active sonar signal processor in use by the U.S. Navy as well as simulations of several systems which are under development. These developmental models include a highly sophisticated model of the serial DIMUS which permits the treatment of any type of plane wave noise field whose spectral characteristics can be specified. Moreover, this model is designed to produce outputs which can be presented on a CRT BTR display for the purpose of conducting observer studies.

## 2.3 Psychophysical Studies

TRACOR has measured the effect of acoustic interference signals on the detectability of targets in a set of psychophysical experiments using simulated active sonar video displays. The work produced significant new information concerning the design of sonar systems and the response of men to sonar signal stimuli.



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The measurement program began by first generating a large amount of simulated sonar data containing various types of interference in carefully controlled and known amounts. The data also contained noise (clutter) and submarine target signals having a variety of known characteristics. These data were presented to a group of 8 trained human observers on CRT displays in A-scan, B-scan, and PPI formats. Display presentations were made to resemble almost exactly those found on the AN/SQS-26 CX sonar. When observers viewed the data they were required to respond regarding their confidence that a target was (or was not) present. Responses were collected and analyzed in a variety of ways. Specific experimental measurements of interference effects were obtained. The experimental results were compared with interference effects that were predicted analytically using the  $\omega$  approach.\* In general the two results were in excellent agreement. A very interesting and useful by-product of this research was the determination of the detection-decision criteria that this set of 8 observers appeared to be using to call targets in the three types of display formats.

#### Data Generation

Sonar data used in the experiments were generated by TRACOR on the UNIVAC 1108 digital computer with a set of specially developed programs.\*\* These programs accept prescribed input parameters that characterize any given operational and environmental condition of interest, and calculate the resulting acoustic signals in amplitude, frequency, and duration that would be expected to exist at the input to the sonar receiving array as a function of time for a full ping cycle. This acoustic data consisted of self-noise, reverberation, and interference signals from up to five other active sonars. The programs

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\*The so-called  $\omega$  approach is an analytical method of predicting performance degradation due to mutual interference. This procedure is explained fully in the Appendix.

\*\*The data generation described is for an active sonar. TRACOR has also conducted extensive psychophysical experiments on various passive sonar displays.



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then performed simulated beamforming, temporal processing, and thresholding of the data to produce a set of signals that represented the marks that should be made on a CRT video display. To the background clutter and interference signals were added (when desired) the marking of a randomly varying submarine echo signal(s) with known display marking statistics. The target position and amplitude was variable from ping to ping to allow simulation of a dynamic encounter. Typically, data were generated to present 24 consecutive ping cycles of an encounter to the observers.

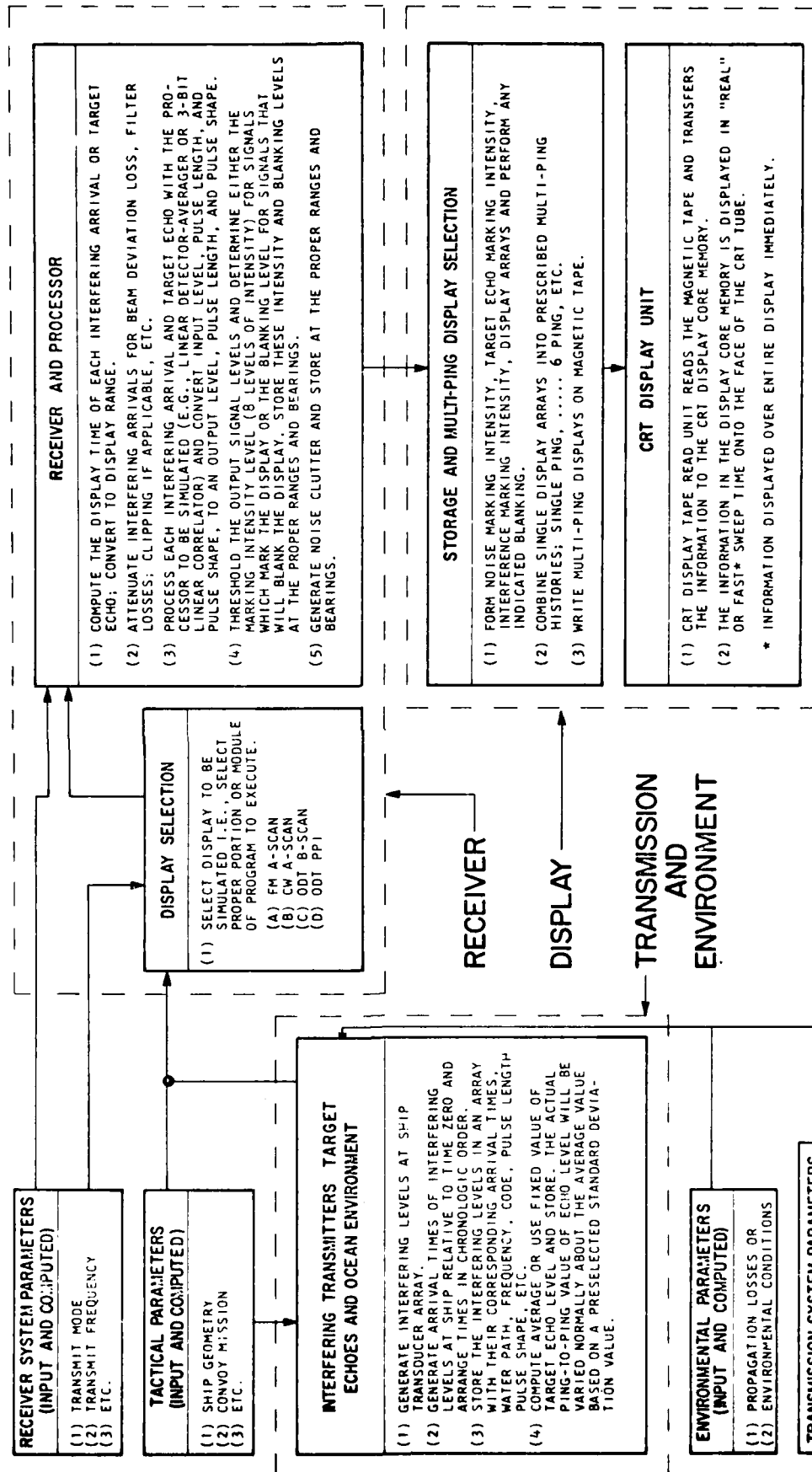
The sonar characteristics built into this simulation were those of the AN/SQS-26 CX. They were determined from extensive analysis of sea data obtained with earlier models of the AN/SQS-26 and data gathered from the CX barge system.

A final step in the data generation process was the forming into either an A-scan, B-scan, or PPI presentation. The formatted data were then stored on magnetic tape for presentation at a later time to the observers.

Figure 4 gives the functional block diagram of the data generation for the case of an AN/SQS-26 MI study.

#### Display Equipment

The data were presented to four observer subjects simultaneously on four standard 17" black and white television monitors in TRACOR's Display Research Laboratory. Sonar data were read off tape by an electronic control unit and routed to a 4k core memory for temporary storage. The control unit was synchronized with the television monitors in such a way that data was extracted from temporary storage, amplified, and applied to the TV CRT's to





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write a completed video picture of a full ping cycle of sonar data in the desired format. The CRT's used were commercial equivalents of the actual shipboard display tubes. A detailed description of this display facility is given in a separate volume of this capabilities series.

### Experimental Procedure

As indicated above, the sonar data presented to the observers typically consisted of 24 consecutive ping cycles of an encounter. The target signal, when present, occurred in 18 of the 24 pings. Many sets of data contained no targets, to gather false alarm data and to prevent the observers from becoming super alerted. When presented with a set of data the observers were required to respond after each ping cycle concerning his confidence that a target was present. A 4-point rating scale response was employed, with the following format:

- 0.....certain no target present
- 1.....possible target present
- 2.....probable target present
- 3.....certain target present

A 1, 2, or 3 response was accompanied by specifying the suspected target's location. A typical experiment consisted of 8 observers responding to 20 different 24 ping cycle runs of a certain type giving approximately 160 independent measurements of target detectability.



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### Data Analysis and Interpretation

Automatic data reduction programs were devised to take the rated responses of observers and to calculate curves of average cumulative probability of detection (at a given confidence level) and probability of false alarm versus time (or ping number) after the target first appeared. By comparing the curves obtained with various types and amounts of interference present to the curves obtained with no interference, we obtained the average increased time to detect a target at a specified probability and confidence level due to the interference. Similarly, we measured the reduced probability of detection at some specified time after the target is first visible on the display. The apparent operator detection decision criteria were obtained by postulating that an observer calls a target when he sees at least  $X$  target marks of a certain brightness in  $Y$  ping cycles. The binomial expansion for this process was used to determine the values for  $X$  and  $Y$  which produced the best fit to the experimentally determined cumulative probability of detection curves. Examples of these curves (solid lines) and experimental points are shown in Figs. 5 and 6.





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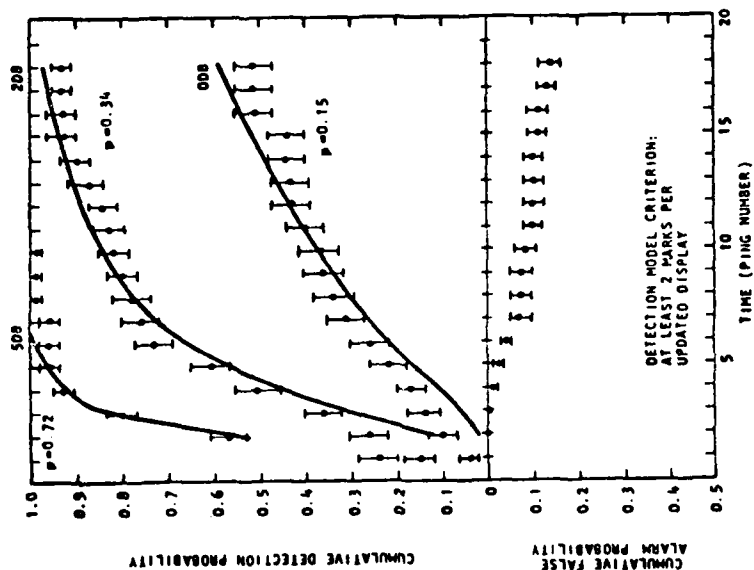


FIG. 5 - OBSERVER PERFORMANCE FOR AN AT LEAST 2 OBSERVER CONFIDENCE RATING AND THE CM/A-SCAN DISPLAY.  $\rho = 0.0$ , FAST RANGE RATE TARGET ECHOES. THESE DATA WERE FIT USING THE DETECTION MODEL DESCRIBED IN THE TEXT (U)

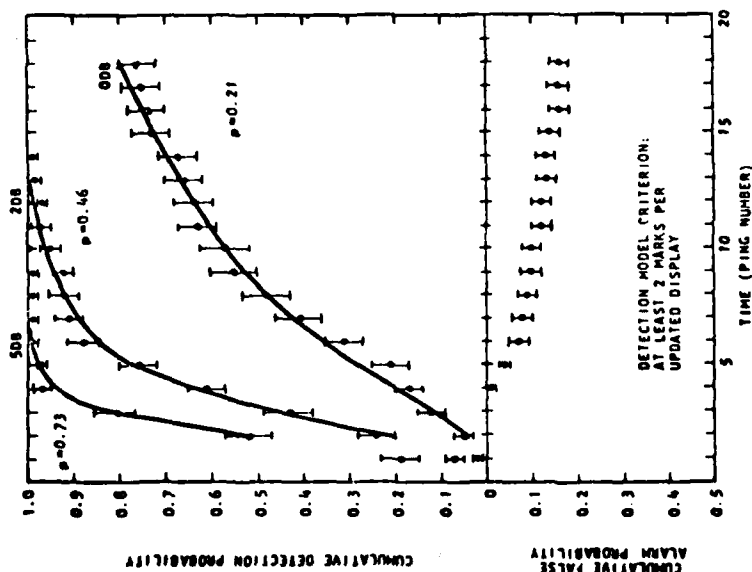


FIG. 5 - OBSERVER PERFORMANCE FOR AN AT LEAST 2 OBSERVER CONFIDENCE RATING AND THE CM/A-SCAN DISPLAY.  $\rho = 0.0$ , SLOW RANGE RATE TARGET ECHOES. THESE DATA WERE FIT USING THE DETECTION MODEL DESCRIBED IN THE TEXT (U)



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### 3.0 RELATED EXPERIENCE

TRACOR's experience falls into four major areas:

(1) sonar countermeasures susceptibility studies, (2) sonar mutual interference studies, (3) ASW systems and tactics trade-off studies, and (4) general underwater acoustics research and development studies. Some specific pieces of work in each category are briefly described below.

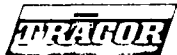
#### 1. Sonar Countermeasures Susceptibility Studies

(a) Under NAVSHIPS Contract N00024-71-C-1356, TRACOR defined the acoustic CM environment that is likely to be faced by AN/SQS-26 equipped destroyer escorts in the mid-1970's, analyzed and determined the susceptibility of the AN/SQS-26 (with certain proposed major modifications) to acoustic countermeasures, and recommended design changes that would "harden" the sonar against countermeasures. Under a mod to that contract, we are presently engaged in planning a sea test program to further investigate the susceptibility of that sonar to acoustic countermeasures. See TRACOR Report T71-AU-7014-S.

(b) Under NUWC Contract N00123-67-C-2964, TRACOR investigated the susceptibility of the AN/SQQ-23 (PAIR) sonar to countermeasures in a study similar to the AN/SQS-26 project described above. See TRACOR Reports 68-711-S(R) and 68-912-S.

#### 2. Sonar Mutual Interference Studies

(a) Under NAVSHIPS Contract NObsr 95149, TRACOR planned, conducted, and analyzed the results of a three ship mutual interference sea test of the AN/SQS-26 sonars on the 1040 class destroyer escorts to determine what interference was present, what was causing the interference, and what could be done to minimize or eliminate it. See TRACOR Report 66-150-C.



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(b) Under NAVSHIPS Contract NObsr 95149, TRACOR analyzed all the acoustic devices that were to be installed on the AGDE-1 (USS GLOVER) to determine the expected sensitivity of the sonars to intership and intraship interference. The systems considered were the AN/SQS-26 (active and passive subsystems), PADLOC passive sonar, AN/SQS-35 (variable depth sonar), WQC-2 (underwater telephone), UQN-1 depth sounder), T-MK6 and NIXIE torpedo countermeasures. See TRACOR Report 69-866-C.

(c) Under NAVSHIPS Contract N00024-69-C-1186, TRACOR developed a simulation of the AN/SQS-26 video displays and a computer program to drive them to simulate sonar performance in the presence of interference. Extensive human factors experiments were conducted to determine experimentally the validity of the  $\phi$  method for quantifying the effects of interference on sonar performance. See TRACOR Report T70-AU-7193-C.

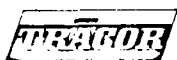
(d) Under Contract N00024-69-C-1186, TRACOR evaluated the susceptibility of the AN/SQS-26 to interference from AN/SQQ-23 (PAIR) transmissions. See TRACOR Report T70-AU-7188-C.

(e) Under NEL Contract N123(953)54996A the susceptibility of the AN/SQQ-23 (PAIR) to intership interference was evaluated. See TRACOR Report 66-635-C.

### 3. ASW Systems and Tactics Trade-off Studies

(a) Under NAVSHIPS Contract NObsr 95149, we used our ASW Engagement Model to determine the cost effectiveness of a number of proposed design changes to the AN/SQS-26 sonar. See TRACOR Report 69-163-C.

(b) Under NAVSHIPS Contracts N00024-69-C-1180 and N00024-70-C-1130, the Engagement Model was used to determine



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recommendations concerning the sonar technology areas in which improvement would produce maximum benefit to the Navy's submarine and surface ship ASW capabilities. See TRACOR Reports 69-662-C and T71-AU-7007, Vol. I.

(c) Under NAVSHIPS Contract N00024-70-C-1062, the Engagement Model was used to determine (1) the effects of inter-ship sonar interference on the overall ASW effectiveness of a multiship force of destroyer escorts, (2) recommendations for certain sonar design changes, and (3) recommendations for operating doctrine of the ships and sonars to maximize effectiveness. See TRACOR Report T71-AU-7018-C.

(d) Under NAVSHIPS Contract N00024-70-C-1266, the Engagement Model is currently being used to assess the ASW effectiveness of destroyer escorts equipped with both the AN/SQS-26 and AN/SQS-35(V) sonars, accounting for the potential mutual interference problems, and developing recommendations for coordinated sonar operating doctrine. Report is not yet available.

#### 4. Related General Studies

(a) Under NAVSHIPS Contracts N00024-69-C-1080, N00024-70-C-1163, and N00024-71-C-1126, TRACOR has developed a baseline performance manual for the AN/BQQ-2 sonar suite consisting of the AN/BQS-6, AN/BQS-13, AN/BQR-7, and the AN/BQQ-3 sonars. See TRACOR Reports 69-832-C and T70-AU-7486-C.

(b) Under NAVSHIPS Contract N00024-69-C-1051, TRACOR developed dynamic detection models and operator detection decision criteria for the AN/BQR-2 and AN/BQR-7 analog systems. See TRACOR Report 69-296-C.



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(c) Under Contract N00024-67-C-1572, the AN/BQR-7 was analyzed to determine the performance gains obtainable by DIMUSizing the '7's beamformer. See TRACOR Report 67-582-S.

(d) Under NAVSTIC Contract N600(63079)65645, TRACOR analyzed the performance of a classified foreign sonar and determined certain conclusions regarding the current enemy threat characteristics. Report not available.

(e) Under NAVOCEANO Contract N62306-69-C-9164, TRACOR investigated techniques for processing bottom reflected signals from explosive sources in support of the Marine Geophysical Survey. See TRACOR Report 69-925-C.

(f) Under NAVSHIPS Contract N00024-70-C-1146, TRACOR generated the technical specification for a AN/BQR-2 (DIMUS) system, and under Contract N00024-71-C-1222 we are now in the process of revising that specification to reflect the results of design studies and updated SSBN threat characteristics.



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Enclosure I

THE TIMFAX SIMULATION PROGRAM



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Enclosure I

THE TIMFAX SIMULATION PROGRAM



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## 1. THE TIMFAX SIMULATION PROGRAM

### 1.1 INTRODUCTION

Since 1960, TRACOR has been involved in the development of mathematical models and simulation techniques for the physical processes and electronic equipments required for realistic radar and sonar analytical studies. The basic tools for these studies have been a large scale digital computer and a general purpose simulation program. The simulation program, TIMFAX, was developed to fit the needs of the electronics engineer and systems analyst that are not adequately considered in the programs written to evaluate analog computers or discrete systems simulations programs such as GPSS. TIMFAX has allowed TRACOR engineers and scientists an easy access to the computational capabilities of the digital computer, and at the same time it has provided a common basis for the comparison of complex systems.

### 1.2 THE TIMFAX LANGUAGE

Every general purpose simulation program creates a programming language. It is the role of this language to translate the commands of the user to instructions that control the operations of the computer. The language effectively serves as an impedance matching device. By this we mean that computers execute very small steps at an exceedingly rapid rate; whereas, the users think in large steps at a much slower rate. For example FORTRAN nearly models the arithmetic expressions used in numerical scientific computation. However, the computer executes many simple operations to evaluate one FORTRAN expression.

Engineering and scientific analysts visualize a system as a complex of interconnected subsystems. The subsystems are further divided into smaller elementary operations. In electronic systems, these smaller units are sometimes given the name "Black Boxes," or sometimes they are given names in common usage, such as low pass filter. The interconnections between boxes are called



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wiring diagrams. These diagrams represent the flow of information, current, or some other suitable function from box to box.

TIMFAX uses this natural language of the analyst to translate the system block diagram into a computer program. This involves the use of two simple types of simple language statements. They are:

- 1) Configuration Statements, which define the inter-connections among the functional blocks and specify the desired functions.
- 2) Parameter Statements, which associate numerical constants with the elements to particularize their functions.

The TIMFAX block-oriented input language has many advantages. Formost, it is user oriented, and requires no more effort on the user than expressing his thoughts in a prescribed fashion. Also, the user can modify his simulation model at the data level by changing a few cards which does not require the services of a professional programmer. Since it is quite easy to simulate a complex system by combining a number of boxes which perform elementary operations, it is practical to sub-partition a system model all the way down to rectifiers. The amount of professional programming labor required to construct these boxes is quite small. Also, many of these elementary operations are common to most systems. The boxes for these elementary operations can be stored in a library and new systems can be simulated quite rapidly.

Examples of TIMFAX language statements will be shown in a later section.

### 1.3 TIMFAX "BLACK BOXES"

As noted above, the TIMFAX "Black Boxes" are a collection of subprograms that model the elementary components of electronic equipments. In the present TIMFAX system, these subprograms are



written mostly in FORTRAN<sup>\*</sup>. Actually, the boxes are FORTRAN Subroutines with a prescribed argument list.

The subprograms do all of the processing of data that flows through the system; the control program merely links them together and controls the flow of data. The programmer writing a subprogram needs only to concern himself with accurately and efficiently implementing the algorithm of the boxes intended operation. The "Black Boxes" programs are written to be generally applicable, and, thereby, they can be collected in a library and made available to other users. The numerical constants input by the parameter statements peculiarizes the operation of each box. For example, an algorithm used to simulate an RC low pass filter would need the values of RC and the sampling interval.

Along with the boxes used to model components of the system, a set of what we can call analysis "Black Boxes" is included in the library. Boxes of this sort are intended to measure desired characteristics at one or more points within the system being modeled. These programs are analogous to the various test equipment that might be used on an actual system. Examples of the analysis boxes are: (1) boxes which compute amplitude and frequency statistics, (2) a box which computes signal-to-noise ratios at any point, and (3) power spectra estimators.

Boxes which compute time functions for the types of deterministic and random signals found in electromagnetic and acoustical systems are included in the library. Another useful set which expands the utility of the program are boxes that transfer data in and out of the system. These boxes allow TIMEFAX to use bulk storage devices such as magnetic tape, drums, and cards that are part of the Computer Equipment configuration. Also, experimental data that has been digitized can be input to the system to evaluate the system model.

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<sup>\*</sup>UNIVAX 1108 FORTRAN V



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#### 1.4 TIMFAX CONTROL PROGRAM

With the "Black Box" library representing on the shelf items such as signal generators, system components, test probes, and output display devices, the control program acts as the patch panel that hooks all of this together. The resulting configuration is known as a "topology."

The first task is to read the configuration statements, syntax check them, and withdraw the needed box programs from the library. The control program then forms a set of instructions that link the boxes together with the proper input, output, and sequence order.

This information is sent to the second part of the control program and is used, in effect, to build a working program. The parameter statements are read at this time, syntax checked, and stored for use by the subprograms. During the run execution the control program monitors the run and manages the flow of data between boxes. All data in and out of the working program as well as the data processing is done by the subprograms.

The working program is divided into control sections that can be used to perform the functions of initialization, processing, and summarizing.

Two types of data are processed by the system; they are: (1) Time Function Data, actually time series, and (2) Field Data. These data types are distinguished by the way they are propagated through the configuration model. Time function data is an ordered set of numerals representing recorded or computed values at discrete intervals of time. Theoretically, the size of the set is unlimited, but meaningful results can be obtained using a finite sample from the set. Generally, even this finite set is of sufficient length to require processing it through the subprograms in a series of sequential segments. The finite set of data is called a record. Any number of records comprise a file. Time



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function data is cycled through the simulation in records. A field is an array of numbers that can be stored in the computer memory at one time. The entire array is available to the sub-program requesting it. This ability to segment a large data base and keep it moving sequentially through the simulation is one of the outstanding features of the system.



## 2. USES OF TIMFAX

### 2.1 INTRODUCTION

There are basically two uses of TIMFAX: systems simulation and data processing. However, these two areas comprise the majority of work done on general purpose digital computers. The system was developed originally to process sonar data (either digitized recorded data or idealized computer-generated data), but it is equally capable of processing any large data base problem which can be digitized.

### 2.2 SYSTEMS SIMULATION

The widest use of the TIMFAX system has been in sonar signal processor simulations. In this case the black boxes model the elementary components of the processor and the topology is the circuit diagram. The flexibility of rearranging the components, or boxes, allows many schemes to be compared and evaluated. Using sea data as an input, a processor can be simulated and the performance of the onboard processor can be estimated.

Figure 1 shows a time function analysis problem that is easily studied using TIMFAX. White Gaussian noise is passed through a band pass filter and then rectified several different ways. Each output is then analyzed to show the probability density and power spectrum. The continuous version of this problem is treated in many books on stochastic processes. TIMFAX has been used extensively to perform analysis on classical problems or actual data from the fields of geophysics, vibro-acoustics, oceanography, and biomedics.

### 2.3 DATA PROCESSING

The features of the system that are used to solve problems in time series analysis can also be used to do the diverse jobs in the field of general data processing. The problems in this field are not changes in the data base but daily changes in the type of processing that is requested. Once a library of boxes is established, the block model structure of TIMFAX would make such changes to the topology simple and less costly.



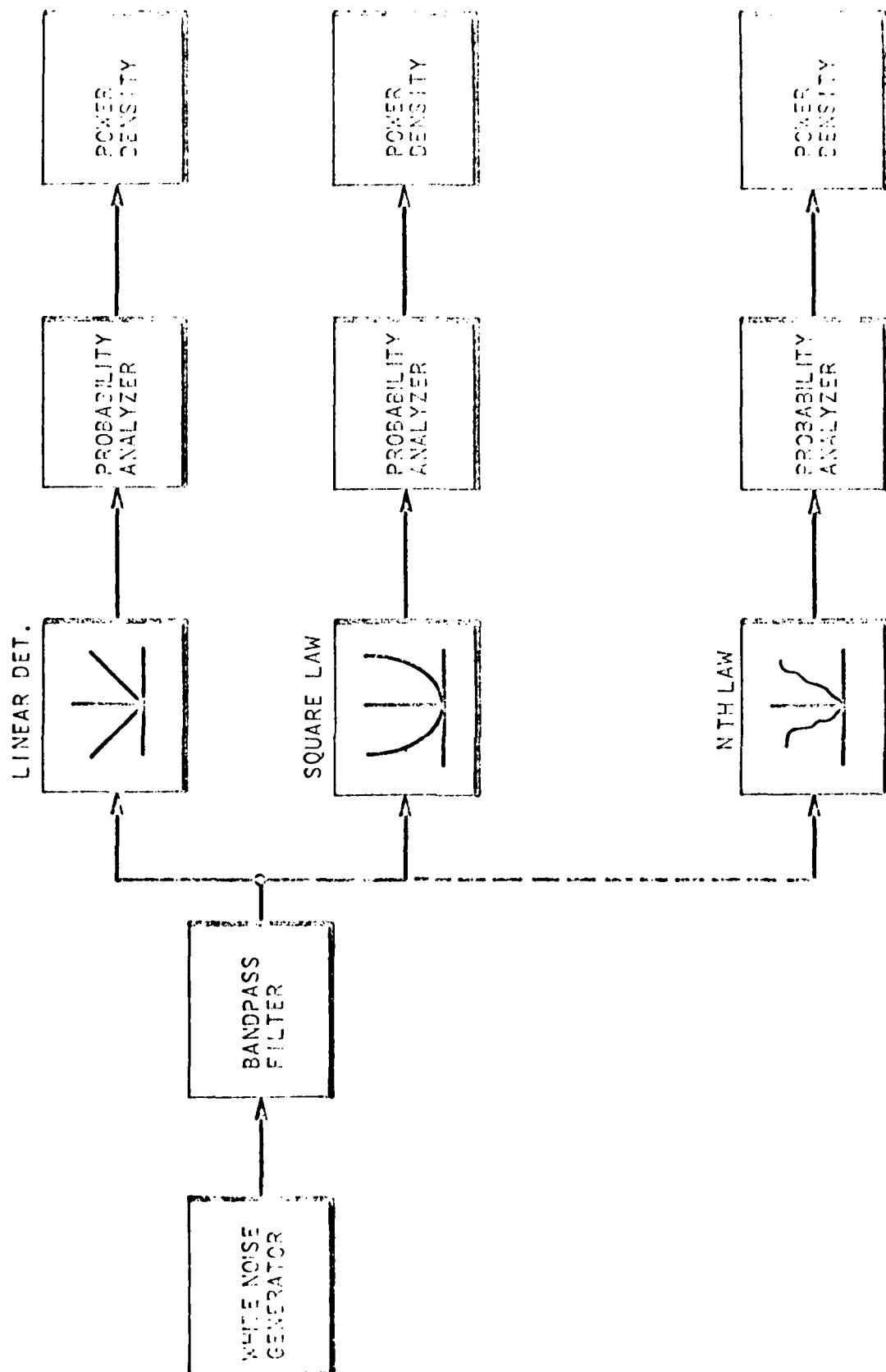


Fig. 1 TIME FUNCTION ANALYSIS PROBLEM



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### 3. THE TIMFAX LIBRARY

There are currently over 100 reentrant subprograms in the black box library. They can be linked together in many different ways, allowing for parallel, serial, and feedback processing of input data. It is noteworthy that the subprograms have been written with an eye to the most recent techniques for achieving increased computational speed and/or efficiency. For example the Cooley-Tukey "Fast Fourier-Transform" algorithm is used in a number of boxes. The majority of these programs were developed for time series applications, but some, such as the Input/Output routines, could immediately be used in other areas.

Attached to this document is a set of abstracts of the current boxes in the library file.

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## A METHOD FOR ASSESSING THE EFFECTS OF MUTUAL INTERFERENCE ON SONAR DETECTION PERFORMANCE

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### ABSTRACT

A method for computing a quantitative measure of the interference caused by the transmission of one or more active sonar systems into the receiver of another system has been developed. This measure is designated  $\phi$ , the average fraction of a sonar display in interference and unavailable for operator use. The quantity  $\phi$  is related to the degradation in the following sonar performance measures: (1) the probability that a target echo marks the display, (2) the observer integration time required for detection in multi-ping sequences, and (3) the equivalent signal-to-noise ratio degradation. The applicability of  $\phi$  for assessing performance degradation into passive receivers is discussed briefly.

### BACKGROUND

Mutual Interference is interference which occurs in one sonar because of transmissions from other sonars operating in the same area or from own ship.

Mutual Interference, capable of degrading the performance of a sonar system, occurs primarily in multi-ship screening operations when one or more sonar systems utilizing the same frequency band must be in operation simultaneously. Such interference has always been a major cause of performance degradation. Degradation caused by mutual interference has increased because of the increased sensitivity, i.e., lower minimum detectable level, (MDL), of many of the recently developed sonar systems. This increased sensitivity allows heretofore rejected, unimportant transmissions outside the passband of one sonar to cause performance degrading interference in another sonar. This additional degrading interference results from that portion of the signal power of an offending transmission that lies in the passband of the receiver.

That mutual interference of either type occurs is readily understood when one considers that an interfering transmission from one sonar system to another need suffer only a one-way propagation loss as opposed to a legitimate target echo which is subject to a two-way propagation loss. Generally, the separation of two sonar systems is less than the range of an expected target; thus, the chance that even an off-band interfering signal is larger than a legitimate target echo is rather high. In order to maintain acceptable performance, a sonar receiver must attenuate these interfering transmissions such that it marks their display with considerably lower probability than that of an expected target echo.

Another example of off-band transmissions, causing performance-degrading interference into a sonar system, is seen in the implementation of multi-sonar suites on the same ship. For example, on a single ship, there may be an active search sonar, a passive search sonar,

a depth sounding sonar, and an underwater telephone. In this case mutual interference caused by a variety of transmissions from one's own ship can occur.

Interfering signals arriving at a receiving array with sufficient level to cause degrading interference consist of direct arrivals, specular reflection arrivals via the ocean bottom,<sup>1</sup> and rumble (i.e., bi-static reverberation) arrivals. These interfering signals may degrade performance in any one of three ways: display marking, display blanking, or AGC blanking.

Display marking occurs when interfering signal levels at the input to the display are high enough to exceed the marking threshold. The marking length (referred to later in the paper as  $\tau_m$ ) is that length of time the signal is greater than the marking threshold, converted to display range.

Display or receiver blanking may occur whenever a clipped signal processor is subjected to high level pulses of a different code than that which the processor is coded to process (e.g., a cw pulse into a clipped correlator coded to process an FM slide). The output of the processor for an unmatched pulse may not mark the display, but this unmatched pulse appears to the coherent processor as a high level background pulse and therefore masks or "blanks" any legitimate simultaneous target echo which would have marked the display.

AGC blanking may occur in any processor as a result of reaction of the AGC to interfering arrivals that are long with respect to the AGC time constant (e.g., rumble arrivals). Rumble arrivals are not exceptionally high level, but their duration and slow variation permit the AGC to follow them and to achieve some degree of normalization at the output of the processor. As the AGC attenuates the rumble arrival to some equilibrium output level, simultaneously arriving target echoes are also attenuated and their output signal-to-threshold ratios are correspondingly reduced.

The quantitative measure of mutual interference should be judged in terms of its effect upon a sonar display because it is at this point where the output data are passed on to the observer. The primary effect of the interference is to put the display in a condition in which it is unable to transfer data to the observer. In effect this is time in which the sonar is not operating. This paper is aimed at assessing these display effects numerically and subsequently using these numerical values to determine the degradation in sonar performance measures.

Historically, mutual interference studies have fallen short of this kind of assessment until the works of Brown,<sup>1</sup> Kostoff,<sup>2</sup> and Gullatt.<sup>3</sup> Previous studies usually consisted of calculating the levels of interfering transmissions at a receiver array and comparing them to the MDL, established for the processor associated with the receiver, to decide whether interference effects should occur. The primary shortcoming of this approach is in neglecting the effect of the processor on the interfering signal. In general, there will be a different MDL for the interference than that expected for a target echo. In addition, it is important to account for the fraction of time the receiver is subject to such interfering arrivals.

Another approach has been to average the power in the interfering arrivals over the entire echo ranging cycle. This, in effect, raises the average power level of the background over the echo cycle, and raises the average MDL. The shift in MDL was then interpreted as the number

<sup>1</sup> Specular arrivals from the ocean surface are virtually superimposed upon the direct arrival for surface ship sonars.

<sup>2</sup> B. M. Brown, and M. R. Kostoff, "Self and Mutual Interference in the Proposed 1-Side A Two-Mode Processing Model," TRACOR Document 66-135-C (Rev) (20 July 1967) (Confidential).

<sup>3</sup> M. R. Kostoff, B. M. Brown, J. J. Dow, and B. C. Hart, "Simulation of the PAIR Active Displays in the Presence of Mutual Interference," TRACOR Document 67-915-C (25 Oct. 1967) (Confidential).

<sup>4</sup> J. H. Gullatt, "Performance Degradation of AN/SQS-26(X) Sonars by Intership Acoustic Interference," TRACOR Document 68-110-C (19 Feb. 1968) (Confidential).

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of decibels of performance degradation and used directly to estimate degradation in detection range.

Although a relationship between detection range degradation and mutual interference was also determined in the papers referred to above (Refs. 1-3), these works also demonstrated that this relationship alone was not sufficient to describe the total effect of interference upon the sonar performance parameters. For example, the approach described in this paper shows that there is a performance degradation at all sonar ranges in addition to the detection range degradation. The present approach also predicts a more accurate value for detection range degradation than the increased MDL method because the latter totally disregards the interaction of the processor and the interfering pulses.

#### ANALYSIS OF MUTUAL INTERFERENCE DEGRADATION

Interference signals capable of marking or blanking the display can prevent some portion of the display from indicating a target that would otherwise be discernible to the operator. This reduces the search coverage of the sonar by reducing the probability that an observer will call a contact for the portion of the display in interference. The analysis described here is aimed at determining the average amount of display which is unavailable to the operator per display sweep and relating this average to the expected probability that a given target echo will mark the display. Since the probability of detection is closely related to the probability that a target echo will mark the display, a degradation in detection performance could be determined if the above mentioned relationship were known.

The probability of detection, as usually quoted, involves the average signal-plus-noise statistics and the time between independent decision opportunities. It therefore represents the average performance over many specific conditions. In the same way, each display sweep involves a specific mutual interference pattern which varies from one display sweep to another if the sonar repetition rates are not identical or if the interfering sonar systems maneuver relative to the receiving system. The assessment of mutual interference should therefore involve the average over the mutual interference ensemble.

The numerical value assigned to the mutual interference caused in one sonar system by other systems is  $\phi$ , the average fraction of the display which becomes unavailable to the operator. A computation of  $\phi$  would be carried out as follows:

1. Determine the interfering level, relative to normal background level, at the input to the processor after accounting for propagation loss, directivity index, and input filters. This must be done for each preformed beam<sup>†</sup> in the sonar suffering interference.
2. Determine the response of the processor to the interference for each preformed beam.
3. Determine the length of time the interfering waveform will mark or blank the display for each preformed beam. This time, converted to display range, will be referred to as  $\Delta$ . Although there is a specific value of  $\Delta$  for each preformed beam, it is convenient to integrate over azimuth immediately. The result of this integration is an average  $\bar{\Delta}_{\text{avg}}$  which is the average range deleted from the useful display in the  $n$ th ping cycle by the  $n$ th interfering arrival. The product of  $\bar{\Delta}_{\text{avg}}$  and the number of resolvable beams is the average area of the display (in bearing  $\times$  range units) made unavailable by the  $n$ th interfering arrival. This approach is convenient since mutual interference signals are usually of such a high level that they mark all beams except those pointed directly at the interfering source in approximately the same manner.

<sup>†</sup>Detection range refers to that range at which the probability of detection is expected to be at least 0.5 under a specified false target rate.

<sup>‡</sup>In a scanning system a more appropriate term would be "each resolvable beam."

4. Compute the value of  $\lambda$  utilizing  $\lambda_{nm}$  from (5). The sum of all the  $\lambda_{nm}$  over many ping cycles divided by the number of ping cycles yields the average value  $\bar{\lambda}$  for the sequence. Figure 1 illustrates this procedure for a Plan Position Indicator (PPI) display over a typical four-ping sequence. The shaded annuli represent those portions of the display range sweep in which the processor output of the interfering signals exceeded a threshold and marked the display. The interference marking is shown as an annulus of width  $\lambda_{nm}$  because, as was stated previously, interference levels are, generally, high in all receive beams, regardless of azimuth. The average value of  $\lambda$  over this sequence is given by

$$\bar{\lambda} = \frac{1}{N} \sum_{n=1}^N \sum_{m=1}^M \lambda_{nm} \quad (1)$$

The  $\lambda_{nm}$  are the individual annuli of interference marking where the index  $n$  refers to ping number and the index  $m$  refers to the  $m$ th interfering arrival in the display, of the  $n$ th ping cycle. For example, in Fig. 2,  $n = 1, \dots, N$  where  $N = 4$  and  $m = 1, \dots, M$  where  $M$  for each display may be different and is the number of arrivals in the  $n$ th display.

If  $\bar{\lambda}$  is now divided by the total display range available for detection, the average fraction of the display lost per sweep is obtained. This fraction,  $\phi$ , is

$$\phi = \frac{\bar{\lambda}}{R} \quad (2)$$

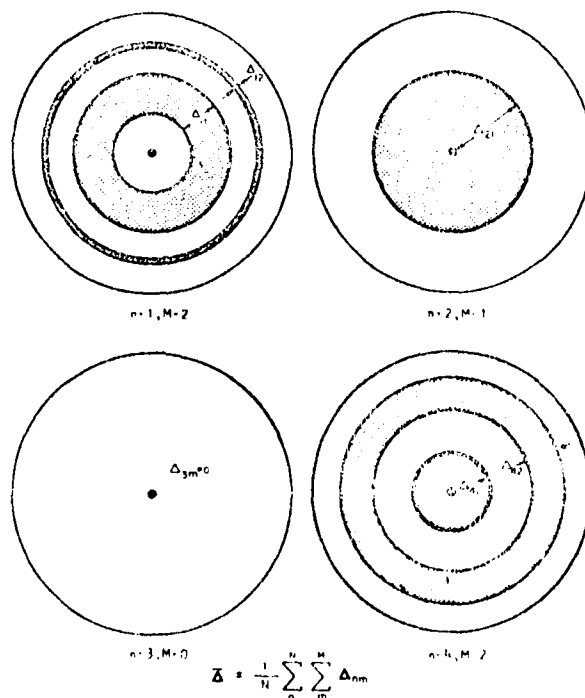


Fig. 1. PPI display illustrating the computation of  $\bar{\lambda}$ , the average value of  $\lambda$  per ping cycle



If it is assumed that the  $\phi_{max}$  will occur at all display positions with equal likelihood, then  $\phi$  may also be interpreted as the probability that a particular point on the display be obscured by interference in a given ping cycle.

#### DERIVATION OF $\phi$ , THE AVERAGE FRACTION OF THE DISPLAY UNAVAILABLE TO THE OPERATOR

A sonar display sweeps in display range from the minimum range,  $r_1$ , to the maximum range,  $r_4$ . The beginning of the display sweep,  $r_1$ , is nearly zero range for non-gated displays, and is the beginning of the display zone for a gated display. The maximum display range is  $r_4$ . The useful range of a sonar display sweep is defined to be that portion of the display in which a target may mark the display with 0.5 probability or greater (i.e., the range interval in which the target echo signal excess is greater than or equal to zero). The range at which the target level curve goes below the MDL (the threshold for 0.5 probability of marking the display) is designated  $r_2$ , the maximum useful display range (see Fig. 2). If the example in Fig. 2 had represented a gated display, the interval of useful range would be  $(r_2 - r_3)$ ,  $r_3$  being the range at which the gated display is turned on provided the signal excess exceeds zero at this range. Hence the useful display range will be given by either  $(r_2 - r_1)$  or  $r_2$  depending upon the display mode.

The first step in calculating the mutual interference into a sonar system is to determine the interference contribution of each offending sonar system into another. The next step is to combine the interference contributions of these systems to find the total interference for multi-system cases. The remarks are appropriate whether two systems on the same ship are considered or whether two systems on different ships are considered.

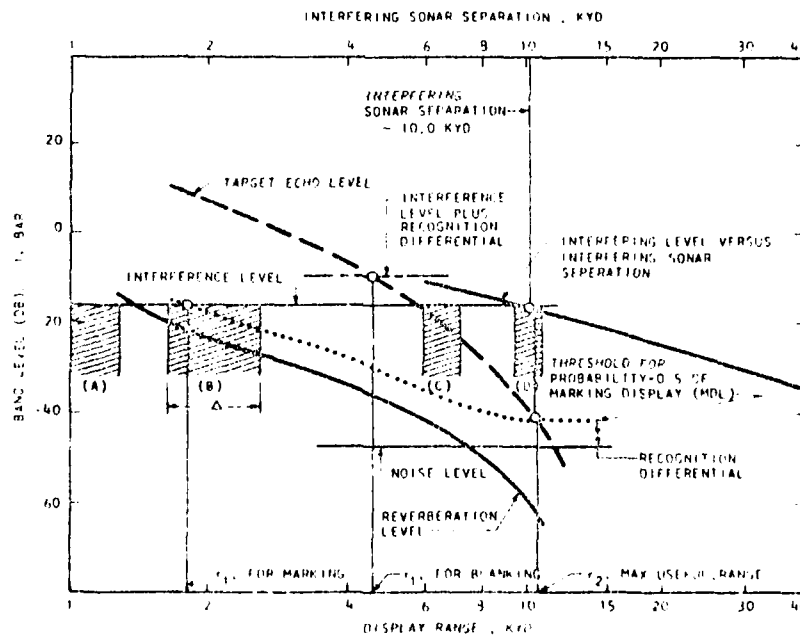


Fig. 2. Example figure for demonstrating  $\phi$  derivation

Figure 2 is a modified version of a typical sonar performance curve and is needed to illustrate the derivation of  $\bar{x}$ . For Fig. 2 the one-way sonar equation for the interfering transmission has been used to determine the interfering level<sup>1</sup> at the processor input. It is plotted as a function of interfering sonar separation.

The target echo level is shown plotted as a function of target range. The reverberation level, the noise level, and the minimum detection level are shown as a function of display range  $r$ . In this diagram, range means either range on the display or target range for all the plots - except one, the interfering level plot. The interfering level plot is shown as a function of interfering sonar separation from the receiving ship. It is clear that the time of arrival of an interfering signal is not related to this separation. In fact, if the interfering ship is at 10 kyd, the interference level is represented by a line parallel to the range axis through the 10 kyd point on the interfering level plot. The interfering transmissions are shown in four positions during the display, denoted by the crosshatched regions (A), (B), (C), and (D). The logarithmic range scale causes equal durations of interference to appear shorter at longer ranges.

The basic assumption in the derivation of  $\bar{x}$  is that the arrival time of an interfering pulse (or its display range equivalent) is a uniformly distributed random variable.<sup>2</sup> For this assumption, the interfering pulse may arrive at any time in the display sweep with equal likelihood, thus modeling a situation where the transmit time of an interfering sonar and the time at which a receiving sonar initiates its display sweep are statistically independent. Further assume that only one interfering pulse will arrive during each useful display sweep interval.<sup>3</sup> In Fig. 2 the shaded rectangles at positions (A), (B), (C), and (D) represent four possible arrival times of an interfering pulse into the display. Any one of these four arrival positions are assumed equally likely to occur. The range equivalent of the interfering pulse length at the output of the processor is denoted by  $\Delta$ , the amount of display range the interfering pulse may mark or blank.

The interference produced by a single interfering arrival averaged over the distribution of arrival times is required in the estimation of  $\bar{x}$ . If any portion of the interfering pulse lies in the useful display range, it is considered to be an interfering arrival. This means that even though an interfering pulse arrives before the display sweep begins, the trailing edge of the pulse may fall within the useful sweep range. Similarly, the leading edge but not the trailing edge of the pulse could fall within the useful sweep range (e.g., the pulse shown in position (D) of Fig. 2, lying across the range  $r_2$ ).

Based on the above assumptions, the density function  $x(r)$  describing the distribution of display ranges at which the trailing edge of an interfering arrival may fall is simply

$$x(r) = \frac{1}{r_2 + \Delta} \quad (3)$$

where  $r_2$  is the maximum useful display range and  $\Delta$  is the same quantity described previously, i.e., the maximum amount of display range in interference in a particular bearing caused

<sup>1</sup>The example in Fig. 2 shows a typical arrival level behavior (e.g., first bottom, self beam, etc. present on) arrival) from a ship at 10 kyd transmitting a 1-sec signal. A different arrival level plot may be made for each type of interference.

<sup>2</sup>This is a valid assumption for the case in which two sonar systems have different transmission periods or where ships maneuver relative to each other. In these instances, over a long period of time, interfering transmissions should have arrived at all portions of the sonar display with equal frequency.

<sup>3</sup>The possibility that either none or more than one interfering pulse can arrive in the useful display interval is accounted for later in Eqs. (9) and (10).

<sup>4</sup>The maximum useful display range,  $r_2$ , is used in this development rather than  $r_d$ , the maximum display range, since by definition target detection in the interval  $[r_2, r_d]$  is precluded; thus, in the "useful display range" sense,  $[r_2, r_d]$  is equivalent to an interval of dead time in the transmission period and therefore contributes nothing to the fraction of useful display in interference.

by a particular interfering transmission. In Fig. 2,  $\Delta$  is equal to the range equivalent of interfering pulse length.

In Fig. 2 it will be noted that  $r_1$  is the value of display range where it is first possible for the trailing edge of the interfering pulse to mark. It is at this range where the interfering arrival first exceeds the marking level. At ranges less than  $r_1$ , the entire interfering pulse level is below the MDL and therefore will not mark the display (position A). (There is a different value of  $r_1$  if the arrival blanks rather than marks the display. The word blank can be substituted for mark in the following discussion if the appropriate  $r_1$  is used.) When the range of the trailing edge of the interfering pulse becomes greater than  $r_1$ , it can mark the display (position B). As the range of the trailing edge of the interfering arrival increases with respect to  $r_1$ , the amount of display which can be marked will increase linearly with slope one, until the display range of the trailing edge is  $r_1 + \Delta$ . At this point the entire interfering pulse length,  $\Delta$ , is in a position to mark the display. If  $\Delta(r)$  represents the marked display range when the trailing edge of the arrival is at  $r$ , then  $\Delta(r)$  rises linearly from zero to  $\Delta$ . When the range to the trailing edge of the interfering pulse is between  $r_1 + \Delta$  and  $r_2$  (position C), the maximum amount of display that can be marked is  $\Delta$ . For ranges between  $r_2$  and  $r_2 + \Delta$  (position D), the amount  $\Delta(r)$  of useful display that can be marked decreases linearly from  $\Delta$  to zero. There may be some portion of the display in excess of  $r_2$  that is marked but this marking is not considered interference because it is assumed no detections can be made at ranges beyond  $r_2$ ; therefore, this region is not included in the interference calculation.

Thus, the amount of the display that will be marked (or blanked) for all possible display ranges at which the trailing edge of the interfering pulse may arrive, is given by Eq. (4):

$$\Delta(r) = \begin{cases} 0 & r \leq r_1 \\ r - r_1 & r_1 \leq r \leq r_1 + \Delta \\ \Delta & r_1 + \Delta \leq r \leq r_2 \\ -r + (r_2 + \Delta) & r_2 \leq r \leq r_2 + \Delta \\ 0 & r_2 + \Delta \leq r \end{cases} \quad (4)$$

This function is plotted in Fig. 3.

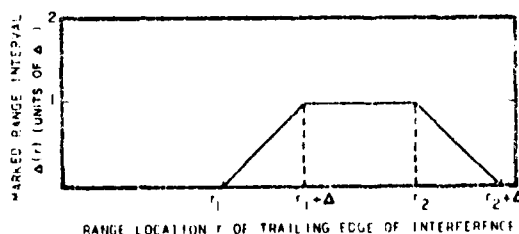


Fig. 3. The amount of useful display marked versus arrival range of trailing edge of interfering pulse

$\Delta(r)$ , given by Eq. (4), is for an interfering pulse with a rectangular envelope.

The interval of display range that will be marked (or blanked), averaged over all possible display ranges at which the trailing edge of the interfering pulse may arrive, is denoted  $\bar{\Delta}_v$ . This is the expectation of  $\Delta_v(r)$  for the beam number  $v$ . The density function describing  $\Delta_v$  was given in Eq. (3) and  $\bar{\Delta}_v$  is given by

$$\bar{\Delta}_v = \int_{r_1}^{r_2} \Delta_v(r) \frac{1}{(r_2 - r_1)} dr \quad (5)$$

With the description of  $\Delta_v(r)$  given in Eq. (4), this integral becomes

$$\bar{\Delta}_v = \frac{1}{(r_2 - r_1)} \left[ \int_{r_1}^{r_1 + \Delta} (r - r_1) dr + \int_{r_1 + \Delta}^{r_2} \Delta dr + \int_{r_2}^{r_2 + \Delta} (r_2 - r + \Delta) dr \right] \\ = \frac{(r_2 - r_1)^2}{(r_2 - r_1)^2} \quad (6)$$

This value of  $\bar{\Delta}_v$  was obtained for a single beam. A value of  $\bar{\Delta}_v$  must also be obtained for each of the other beams;  $\bar{\Delta}_v$  is usually found to be almost independent of bearing except for three or four beams nearest to the azimuth of the incoming interference. The average of  $\bar{\Delta}_v$  across all beams gives  $\bar{\Delta}$ , the average amount of the display marked (or blanked) per beam for the interfering signal. The expression for  $\bar{\Delta}$  is

$$\bar{\Delta} = \frac{1}{L} \sum_{v=1}^L \bar{\Delta}_v \quad (7)$$

In Eq. (7),  $L$  is the number of preformed receiving beams. Because the beams fall generally into two categories of interference with only two distinctly different values of  $\bar{\Delta}_v$ , this average is usually a trivial computation: very often  $\bar{\Delta} = \bar{\Delta}_v$  for a beam pointed away from the interfering source.

The expectation of the fraction of useful display marked by interference per interfering pulse, of length  $\Delta$ , is obtained by dividing  $\bar{\Delta}$  by the useful range  $(r_2 - r_1)$ , i.e.,

$$\frac{\bar{\Delta}}{(r_2 - r_1)} = \frac{(r_2 - r_1)^2}{(r_2 - r_1)(r_2 - r_1)} \quad (8)$$

The average fraction of useful display marked per useful display sweep is obtained by multiplying Eq. (8) by the number of interfering arrivals of length  $\Delta$  expected per useful display sweep. This quantity is given by

$$\frac{r_2 - r_1}{R_1} \quad (9)$$

where  $r_2$  is the maximum useful display range and  $R_1$  is the display range equivalent to the interfering ship transmission period.

The resultant expression is denoted  $\bar{\alpha}$ , the average fraction of useful display marked (or blanked) per display sweep by interfering arrivals of length  $\Delta$ :

$$P = \frac{(r_2 - r_1)^2}{(r_2 + r_1)^2} \frac{U_1}{U_2}$$

$$\frac{r_2 - r_1}{(r_2 + r_1) R_1}$$

(10)

If  $r_1 = r_0$ ,  $r_2 = r_0$ ; or if  $r_1 = r_0$ ,  $r_2 = r_0$ ; and if the display is non-gated,  $r_2 = r_0$ .

The numerator in Eq. (10),  $(r_2 - r_1)^2$ , is simply the area under the curve,  $\lambda(r)$ , given in Eq. (4) and plotted in Fig. 3. For all arbitrary output pulse forms,  $\lambda$  will be given by

$$\lambda = \frac{1}{L} \sum_{i=1}^L \frac{\int_0^{r_2} \lambda_i(r) dr}{(r_2 - r_1) R_1} \quad (11)$$

provided that the density function describing  $r$  is uniform. In this expression  $L$  is the number of preformed receiving beams,  $(r_2 - r_1)$  is the useful display range, and  $R_1$  is the display range equivalent of the interfering ship transmission period.

Although Eq. (10) is computed for a rectangular output pulse, it can be shown that Eq. (10) is a good approximation for  $\phi$ , regardless of output pulse form, if  $(r_2 - r_1) \ll R_1$  and  $r_1 \gg r_0$ . The greatest relative error is introduced by this approximation when  $(r_2 - r_1) = R_1$ ; however, cases of this type result in small values for  $\phi$  and the absolute error introduced is negligible.

The above conditions are generally satisfied by direct and specular interfering arrivals, but not by rumble arrivals. For rumble  $r_1 \approx r_2$  and normally  $r_1 \approx (r_2 - r_1)$ , therefore, the function  $\lambda(r)$  needs to be determined. This can be done quite simply using graphical techniques in conjunction with a performance curve, such as Fig. 2. The subsequent integration of Eq. (11) can be easily accomplished with numerical methods to determine  $\phi$ .

The value of  $\phi$  is computed differently for interfering pulses that blank, but the expression for  $\lambda$ , Eq. (10), remains the same. For blanking, a different value of  $r_1$  is required. To determine  $r_1$  for blanking, one locates the display range at which the interfering pulse level plus the recognition differential is equal to the target level (see  $r_1$  for blanking on Fig. 2). For display ranges greater than  $r_1$  for blanking, the interfering pulse will reduce the target level to background ratio of a simultaneously arriving target echo below the minimum level necessary for 0.5 probability of marking. This statement applies to systems that have been modified by clipping.

In addition to being the measure of the fraction of useful display lost in interference per useful display sweep,  $\phi$  may also be thought of as the probability that a particular point on the display will be marked or blanked in each display sweep. In order to preserve situational awareness at all ranges, it is important that the position of interference "walk through" the display in a sequence of pings to assure a uniform distribution of interference positions.

It is necessary to make use of the probabilistic interpretation of  $\phi$  to determine the total interference from interfering pulses arriving from the same system, from different systems, and from rumble arrivals, and for interfering pulses arriving from different radar systems.

The total interference into the  $i$ th system shall be denoted  $\phi_i$ . The total interference into the  $j$ th system from the  $i$ th system shall be denoted  $\phi_{ij}$ , where

$$\phi_i = \sum_{j=1}^N \phi_{ij} \quad (12)$$

and  $k = 1, 2, \dots, M$  corresponds to direct, specular, second order specular, tumble, and so on, interfering pulses arriving at the  $i$ th system from the  $j$ th system, and  $\tau_{i,j,k}$  is the  $\tau_i$  computed for a particular type of arrival. The  $\tau_{i,j,k}$  are summed because most generally they measure mutually exclusive events.

The total interference into the  $i$ th system  $\tau_i$  as a result of all the  $\tau_{i,j}$ 's is given by

$$\tau_i = 1 - \prod_{j=1}^N (1 - \tau_{i,j}) \quad (13)$$

because the  $\tau_{i,j}$ 's measure independent events. Each of the  $(1 - \tau_{i,j})$  factors is the probability that a point on the  $i$ th system's display is not in interference caused by an arrival from the  $j$ th system. The product of all the  $(1 - \tau_{i,j})$  factors is the probability that a particular point on the  $i$ th system's display is not in interference caused by any of the other systems.

Thus, the total interference into the  $i$ th system as a result of all interfering signals from all of the other  $(N - 1)$  systems being considered is given by

$$\tau_i = 1 - \prod_{j=1}^N \left( 1 - \sum_{k=1}^M \tau_{i,j,k} \right) \quad (14)$$

The procedure which has been outlined seems rather complex to instrument but it has been the basis of mutual interference studies in which the interfering arrival structures from a number of ships were developed in a digital computer. Signals, background, and interference marks were placed on the display to estimate observer degradation in the presence of mutual interference. The first results indicate the attractiveness of  $\tau_i$  as a parameter for specifying the effects of mutual interference. When the interference is of the blanking variety,  $\tau_i$  seems to be adequate.

There is some evidence, however, that the predicted  $\tau_{i,j,k}$  are a little small to account for observer performance when the interference marks the display.

## PERFORMANCE DEGRADATION

There are several methods by which one may assess the performance degradation based upon  $\tau_i$ :

1. The factor  $\tau_i$  itself represents the average fraction of the display not available to the operator. It is therefore a satisfactory indication of the severity of mutual interference.

When one utilizes  $\tau_i$  as a measure of interference, careful interpretation is necessary, because  $\tau_i$  is a time average over many events. Therefore,  $\tau_i$  can give no deterministic or instantaneous information unless additional conditions are known. For example, there may be a situation where in two out of three ping cycles no interference is observed, while 30 percent of the display is marked by interference in the third ping cycle. For this example  $\tau_i$  is 0.10, but the value of  $\tau_i$  gives no information regarding ping-to-ping fluctuation of interference nor the number of pings displaying interference sequentially.

2. When averaged over many pings,  $\tau_i$  can be interpreted as the fraction of time cycles which is unavailable to the operator. If  $T$  is the time required to achieve detection in the presence of interference (when a fraction  $\tau_i$  of the clock time or the ping cycles is unavailable) and  $T_0$  is the time required to achieve detection without interference, it is expected that  $T$  can be no less than

$$T = \frac{1}{1 - \pi_1} \quad (15)$$

The ratio of  $T$  to 1 is the average factor by which observation time must be increased to maintain performance at the onset of mutual interference. This ratio is  $1/(1 - \pi_1)$ .

3. A lower limit to mutual interference expressed in equivalent input signal-to-noise ratio can be approximated in decibels by

$$\left(\frac{S}{N}\right)_{\text{input}} = -5 \log(1 - \pi_1) \quad (16)$$

This expression gives the change in input signal-to-noise ratio which is usually associated with increased display integration time by a factor  $T$  to  $T_0$ . In this case  $(1 - \pi_1)$  is the fractional loss in display integration time. Increasing input signal-to-noise ratio by  $-5 \log(1 - \pi_1)$  approximately restores the effective output signal-to-noise ratio to its pre-interference value. It must be remembered that this degradation would be a good approximation only if the mutual interference did not prevent effective use of the display as an integrator, a subject still under investigation.

4. Change in the probability that a target mark can be observed as a result of mutual interference is also a suitable measure of performance degradation. If  $P$  represents the probability that a target mark is made without interference, then, since  $\pi_1$  is the average fraction of the display unavailable to the operator, the probability  $Q$  that a target can be observed in the presence of mutual interference is

$$Q = P(1 - \pi_1) \quad (17)$$

While these four methods of designating the extent of mutual interference are not exact equivalents, they are related. The last of the four methods is by far the most attractive because it relates quite nicely the statistical nature of  $\pi_1$  to the probability that a target echo will produce an observable mark on the display. Since probability of detection must be related to the probability that a target echo mark may be observed, it may be possible to relate  $\pi_1$  to the probability of detection whenever the detection criterion for a particular display is well enough specified.

The discussions thus far concerning the derivation of and subsequent use of  $\pi_1$  to measure the performance degradation in a sonar system due to mutual interference have been limited to active systems. Everything that has been said, however, is applicable to passive systems with slight modifications.

For example, method (2), which assesses performance degradation in terms of a loss of observer integration time, is particularly applicable to passive bearing-time-recorder (BTR) displays. In this case  $\pi_1$  would represent the average fraction of integration time lost in interference rather than display range lost in interference.

## SUMMARY

The superiority of the  $\pi_1$  calculation over the other methods referred to earlier for measuring the extent of mutual interference into a sonar system manifests itself in the following ways:

1. The  $\pi_1$  calculation considers very explicitly the effect of processor gain on interfering signals and then their extent of display marking. This approach takes into account all aspects of processor performance (e.g., clipping, over-averaging, and so on of interfering signals) with the net effect that the predicted overall effect of interference may be reduced.

2. The statistical nature of  $\phi$ , i.e., that  $\phi$  is an expectation which may be interpreted as a probability measure for a Bernoulli process, in which one considers whether a particular point on the display will be lost due to interference, allows the computation of a composite  $\phi$  for one system as a result of interfering transmissions from several other systems.

3. The  $\phi$  calculation is readily implemented for computation with a digital computer for any configuration of interfering systems and ship geometry.

4. The assessment of performance degradation can be expressed (a) directly in terms of  $\phi$ , (b) in terms of increased display integration time to restore performance to the pre-interference level, (c) approximately in terms of equivalent increase in input signal-to-noise ratio to restore performance to preinterference levels, and (d) in terms of degradation of the probability that an observable mark will appear on the display.

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